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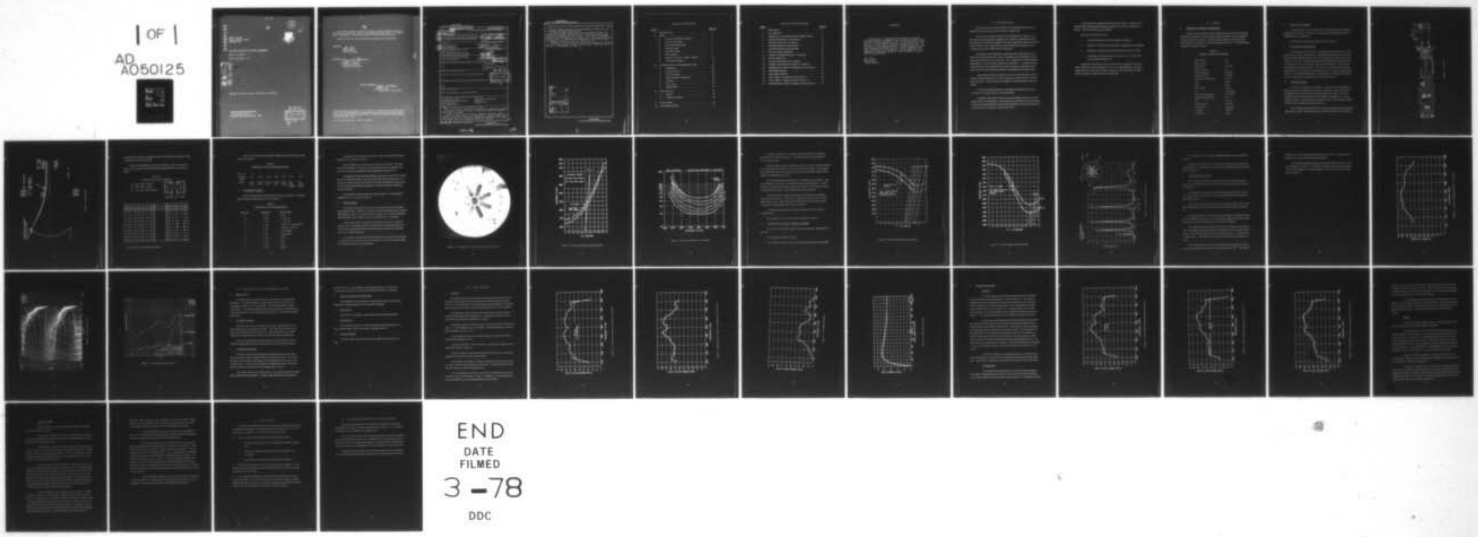

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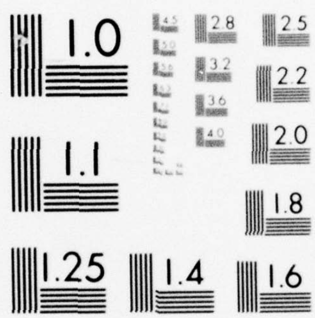

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RADC-TR-77-387
Final Technical Report
December 1977

KLYSTRON-TWT-HYBRID EFFICIENCY IMPROVEMENT

Robert J. Butwell

Varian Associates, Inc.

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report covers a theoretical and experimental investigation of methods of improving the conversion efficiency of S-band Klystron-TWT Hybrid approximately 1 MW of peak power.

The "short stack" intense interaction cloverleaf structure was further developed as the output section of an S-band Twystron. Additional mode loading cavities were added. The coupling slot lengths were lengthened. The two high level bunching cavities in the Klystron section were modified. →

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The gun used in prior work was modified to improve the beam-circuit interaction.

Computer-aided calculations predicted 37% minimum efficiency over a 10% bandwidth with a midband efficiency of 51%.

The additional mode loading rendered the tube absolutely stable. The elimination of the higher order mode in the two klystron cavities provided a significant improvement in the gain response. The increase in slot lengths seemed to reduce the magnitude of the efficiency dip. The gun modification and the increase in slot length worsened the beam-circuit interaction as judged from measured efficiencies of only 3/5 of those predicted.

Performance at the design voltage and current is representative of performance in all regions tested. The swept response showed a midband efficiency of 27% with a 1.5 dB bandwidth of 325 MHz.

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EVALUATION

This effort is in support of the requirements of TPO R4B The tube developed is intended for use in radar transmitters which require up to 10% bandwidth at S-band. The primary thrust of this work is to increase the efficiency of the power output tube. This efficiency is very important because it directly relates to lightweight systems, lower operating costs, and more operating time with a given amount of prime energy. The wide bandwidth is also important to allow radar systems to function properly in today's hostile ECM environment.

Leon Stevens
LEON STEVENS
Project Engineer

I. INTRODUCTION

This final report on Contract F30602-76-C-0130 describes work accomplished during the period 6 July 1976 through 12 August 1977.

In general, the program consisted of the continuation, as Phase III, of a theoretical and experimental investigation into methods of improving the conversion efficiency of relatively broadband linear-beam amplifiers at peak power levels in the vicinity of 1 MW. Specific efforts were directed to the solutions of four problems present in the Phase II experimental tube.

The program effort included the modification and re-optimization of the Phase II cloverleaf design with a view to eliminating a dip in the efficiency which was present near the low end of the band. The re-optimized cloverleaf design was then utilized in a series of paper designs of the Twystron®. A computer analysis was performed on each design and the computer predicted, large signal performance was then used to guide the sequence of modifications of the paper design.

Mode loading cavities were added to one more cloverleaf cavity to inhibit the drive induced oscillations that were detected on the Phase II tube at and just above saturation. These cavities were designed to be tunable under hot test conditions.

A cold test and analysis effort was undertaken to determine the cause of a 30 dB hole in the gain response of the Phase II tube.

A magnetic field study was made and the gun polepiece modified to provide a beam with a 65% filling factor. This modification was made to increase the beam-circuit interaction and bring the measured peak efficiency from the measured value of 41% closer to the computer predicted value of 51%.

A final design was completed and the Twystron was built. Testing was performed at the design operating conditions and then over a range of operating conditions. The test results have been analyzed.

The goals of the program were:

1. Complete elimination of any drive induced oscillations.
2. Elimination of the efficiency dip at the low frequency end of the band.
3. Elimination of the gain hole at the high frequency end of the band.
4. An increase in efficiency from the measured 41% to a value closer to the computer-predicted 51%.

Attainment of the above four goals would provide a constant rf drive bandwidth of 10% with a minimum efficiency close to 40% within that band. The experimental vehicle is a short-stack, intense-interaction, cloverleaf Twystron with a seven cavity klystron input section and a gridded gun.

II. DESIGN

A. PRINCIPAL OPERATING PARAMETERS

Except for minor changes in beam voltage and current, the basic operating parameters remained as for the previous program, Phase II, to be in a region of practical interest to the USAF. Potential system interfaces recommended that beam voltage be increased to 83 kV and the beam current to 38 A. Principal design parameters are given in Table 1.

TABLE 1

PRINCIPAL DESIGN PARAMETERS

Beam Voltage	83 kV
Beam Current	38 A
Beam Power	3.15 MW
Microperveance	1.59
Center Frequency	3300 MHz
Bandwidth (1 dB)	330 MHz
Power Output (Band Edge)	1.2 MW
Gain	30 dB
Duty	0.001
Pulse Width	10 μsec
γa	0.958 radian
$B_e d$ (Klystron Cavities)	1.50 radian
R/Q (Klystron Cavities)	120
Bq	19.5° /in
Brillouin Field	570 gauss
Design Field	1250 gauss
Grid Bias	-1000 V
Grid Pulse	2500 V

B. OVERALL TUBE DESIGN

The specific design, in the sense that it is an S-band Twystron, remained unchanged from Phase II. The details of completely unchanged subassemblies are included below for completeness.

A reduced copy of the layout drawing is shown in Figure 1.

C. GUN DESIGN MODIFICATIONS

The gridded gun, a design used on a megawatt S-band Twystron, was modified to provide a larger diameter beam. Magnetic field measurements were made with the original polepiece design and the outer flux tube was found to have a final diameter of 350 mils. The input polepiece aperture diameter was increased from 2.750 inches to 2.950 inches and the magnetic field remeasured. The outer flux tube diameter increased to 400 mils. See Figure 2. This should provide a beam diameter of 415 mils which gives a filling factor of 0.66. The main operating parameters of the gun remained unchanged. The forward μ is 30 and the gun will operate over a wide range of perveances in the 70 kV to 90 kV area.

D. KLYSTRON DESIGN

The klystron section has seven cavities. The first five are broadband tunable and may be remote tuned while the tube is operating. The last two cavities are inductively tuned for high level bunching and have trim tuners. These two cavities, which are virtually identical, each supported a distorted TE_{11} coaxial mode at 6850 MHz. This mode had strong axial E-fields. This mode also coupled cavities 6 and 7 through the connecting drift tube.

The 30 dB gain hole at 3420 MHz was caused by second harmonic interaction with this TE_{11} mode. Cavity modifications to shift this mode out of the band were

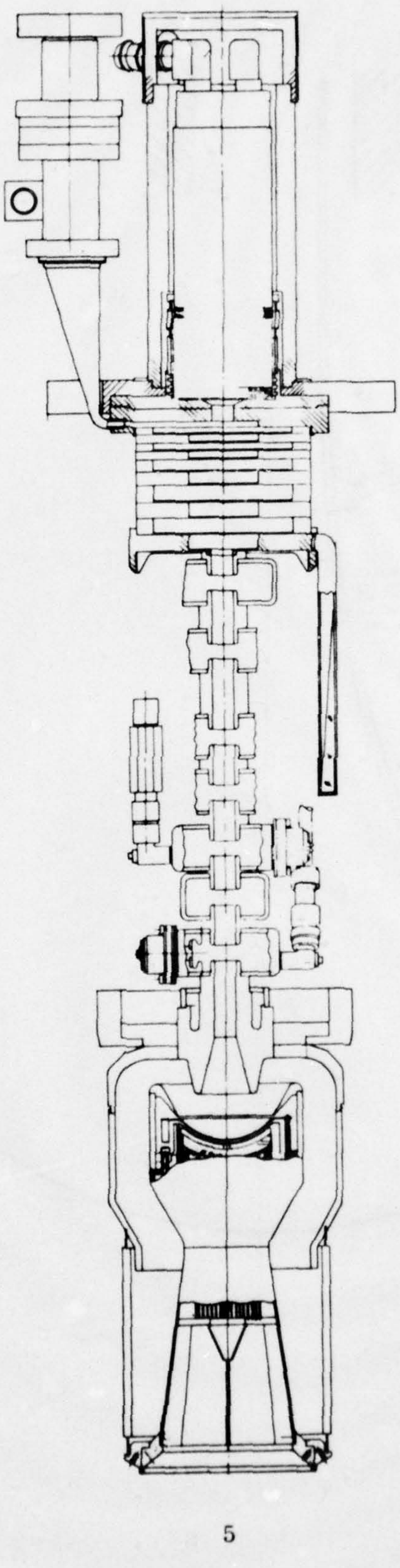


Figure 1. Tube Outline

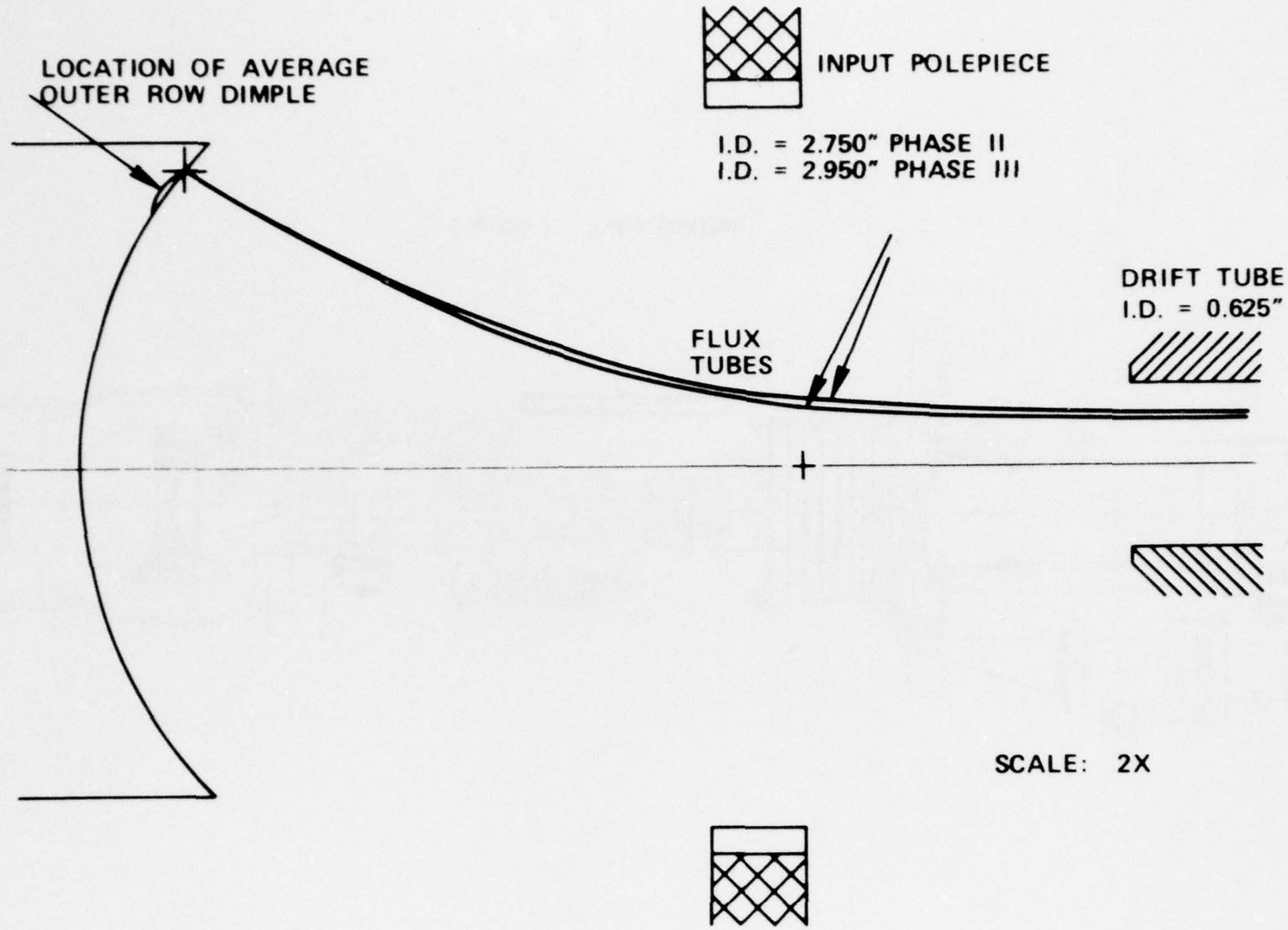


Figure 2. Flux Tube Plot

restricted by the presence of another mode at 6215 MHz and the necessity to keep the fundamental mode at 3520 MHz.

Variation of frequencies, with cavity dimenions, of the main mode; the distorted TE_{11} coaxial mode and the relatively weak split mode; are shown in Table 2.

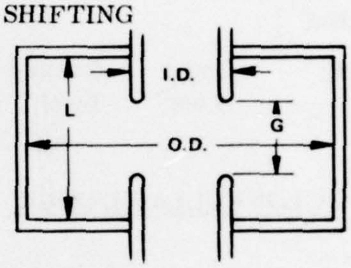
TABLE 2

KLYSTRON CAVITY MODE SHIFTING

F_M - Main Mode Frequency

F_S - Split Mode Frequency

F_T - TE_{11} Coax Mode Frequency



Drift Tube I.D. - 0.625"

O.D.	L	G	I.D.		F_M	F_S	F_T	
Inches	Inches	Inches	Inches		MHz	MHz	MHz	
1.815	1.200	0.432	0.760		3505	5997	6850	
1.750	1.164	0.400	0.760		3560	6412	6960	
1.750	1.200	0.400	0.760		3484	6262	6889	
1.750	1.200	0.432	0.760		3604	6308	6968	
1.750	1.247	0.436	0.760		3522	6125	6882	
1.750	1.247	0.456	0.760		3571	6140	6903	
1.750	1.287	0.436	0.760		3466	5997	6832	
1.750	1.327	0.436	0.760		3397	5868	6755	
1.700	1.200	0.400	0.760		3552	6307	6951	
1.700	1.200	0.400	0.700		3515	6254	6944	*

* Final Dimensions and Mode Frequencies

The pre-set frequencies and external loading of the seven klystron cavities are shown in Table 3.

TABLE 3

FREQUENCY AND LOADING DISTRIBUTION

Cavity No.	1	2	3	4	5	6	7
Frequency (MHz)	3147	3356	3278	3433	3468	3515	3525
Loading	Input Loop	Coaxial Load	Coaxial Load	Coaxial Load	Light Kanthal	Very Light Kanthal	Very Light Kanthal

E. CLOVERLEAF DESIGN

The cloverleaf output circuit consists of eleven circuit plates. The distribution of these circuits by type is shown in Table 4.

TABLE 4

CLOVERLEAF CAVITY DISTRIBUTION

Cavity No.	Height (In.)	Mode Loading
11	0.500	Sever
10	0.500	π, Slot, 5H
9	0.500	π, Slot, 5H
8	0.500	π, Slot, 5H, Light Kanthal
7	0.500	Tunable π, Slot, 5H
6	0.437	Light Kanthal
5	0.375	Light Kanthal
4	0.375	None
3	0.312	None
2	0.250	None
1	0.225	Output

A photograph of a full-height cavity with π point, slot mode and 5H mode loading cavities is shown as Figure 3.

The slot lengths in the velocity taper section were modified. They were increased in length by 5 to 20 mils. The measured decrease in impedance was 10% and the efficiency predicted by large signal analysis dropped by 6%.

The object was to eliminate the efficiency dip, at the low end of the hot band, observed on the Phase II tube. Since the cause of the dip was not known to a certainty, an overall lowering of the pass band was also accomplished to ease the dip to a lower and less objectionable frequency, in case the slot taper modification did not eliminate it.

The dispersion characteristics are shown in Figure 4. The interaction impedance (at r = a) is shown in Figure 5.

F. MODE LOADING

The Phase II tube had three of its five full height cloverleaf cavities with mode loading cavities. While the tube was free from oscillations under most operating conditions, there were conditions of beam voltage, microperveance and magnetic field under which oscillations were present near and at rf saturation.

It has been decided to incorporate mode loading cavities in a fourth full height cavity. A full height cavity was machined with mode loading cavities and the frequency tuning posts of the mode loading cavities mounted on a diaphragm with a simple tuning mechanism.

The tunable cavity was brazed and the tuning posts cycled 40 times through a $\pm$ displacement four times as large as necessary for the requisite tuning ranges. The assembly retained its vacuum integrity.

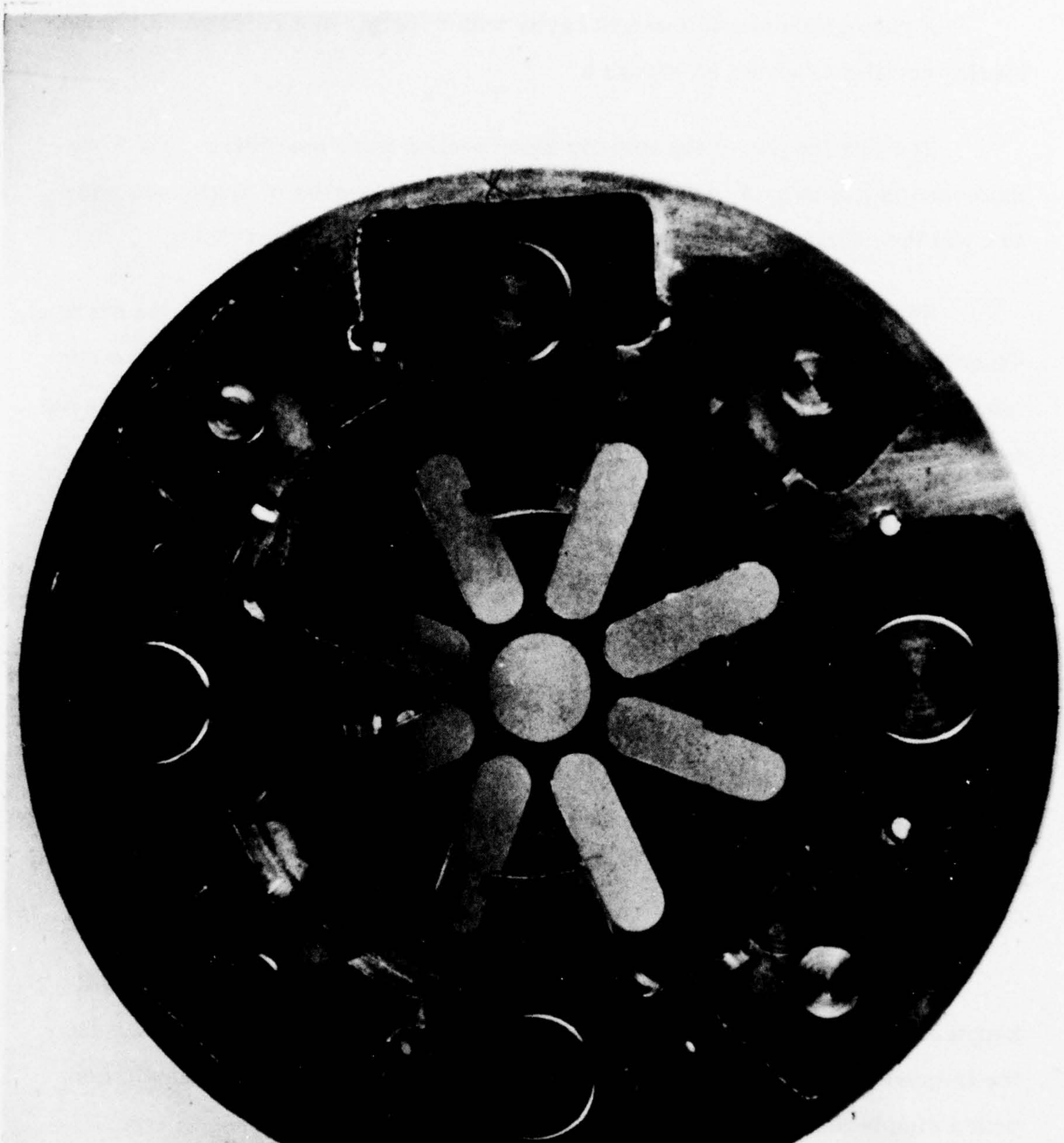


Figure 3. Photograph of Cloverleaf with Mode Loading Cavities

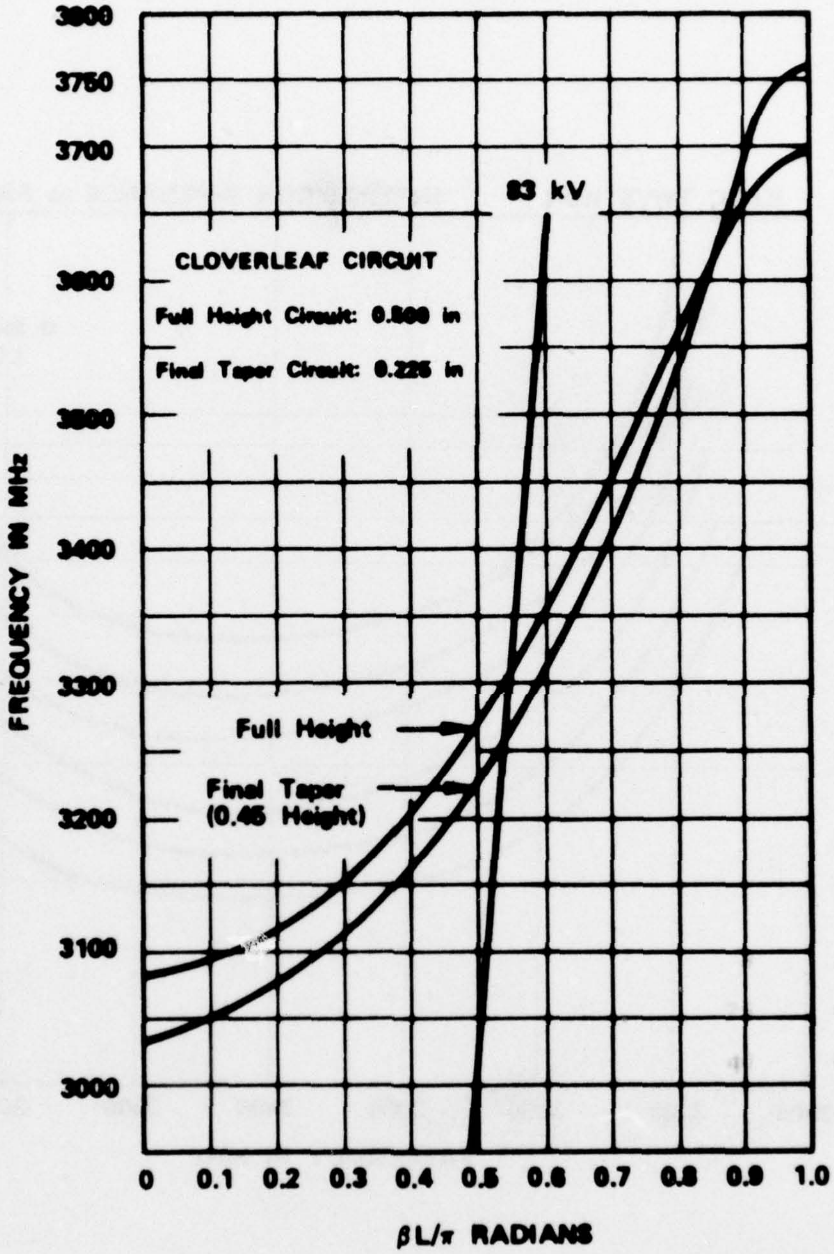


Figure 4. Main Mode Dispersion Characteristics

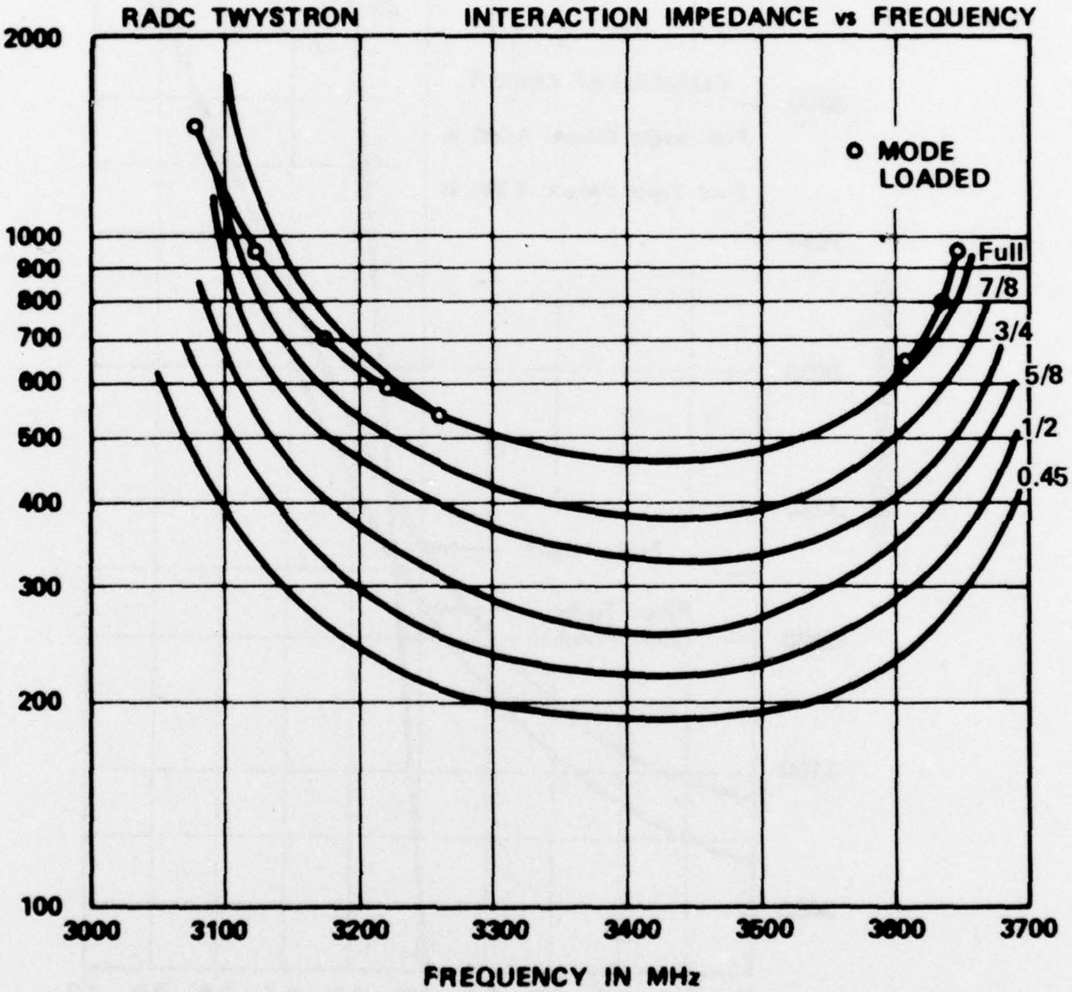


Figure 5. Interaction Impedance vs Frequency

The highest loaded Q for a resonance in either the slot or 5H mode was approximately 80 in the Phase II tube. The highest loaded Q is approximately 60 in the Phase III tube.

While this improvement is significant in itself, the major benefit will accrue from the tunability under hot test of one set of the loading cavities. Any weakness in the loading pattern will be evidenced in hot test, and the tunable cavities can be shifted to strengthen the weak area.

The Phase II tube could only be made to oscillate at the main mode π point at low voltages, 20 kV to 40 kV, and high perveance, approximately 2.0. These results were achieved with a well matched load, however, and it would be of value to enhance the main mode π -point stability against load mismatch.

The inclusion of four additional loading cavities has made it possible to increase the main mode π - point loading to reduce the loaded Q from 76, in the Phase II tube, to 44. Again, the major benefit will be derived from the ability to tune these loading cavities under hot test conditions.

The dispersion characteristics of the slot and 5H modes are shown in Figures 6 and 7.

The resonances of a 6-resonance stack are shown in Figure 8.

G. <u>COUPLERS, COLLECTOR, WINDOW, SOLENOID</u>

The sever has an inductive coupler and is terminated in a matched load of BeO-SiC.

The output has an inductive coupler.

The collector is water-cooled and electrically isolated from the tube body.

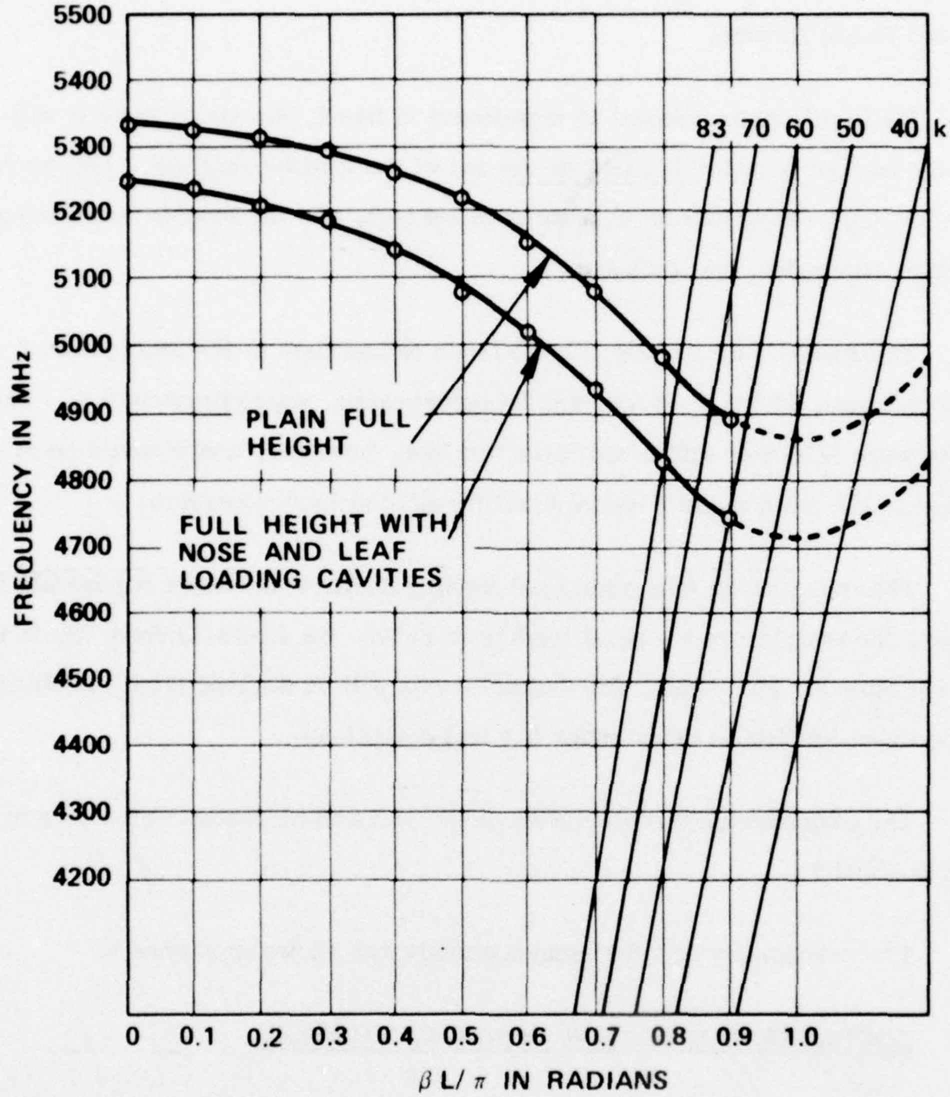


Figure 6. Slot Mode Dispersion Characteristic

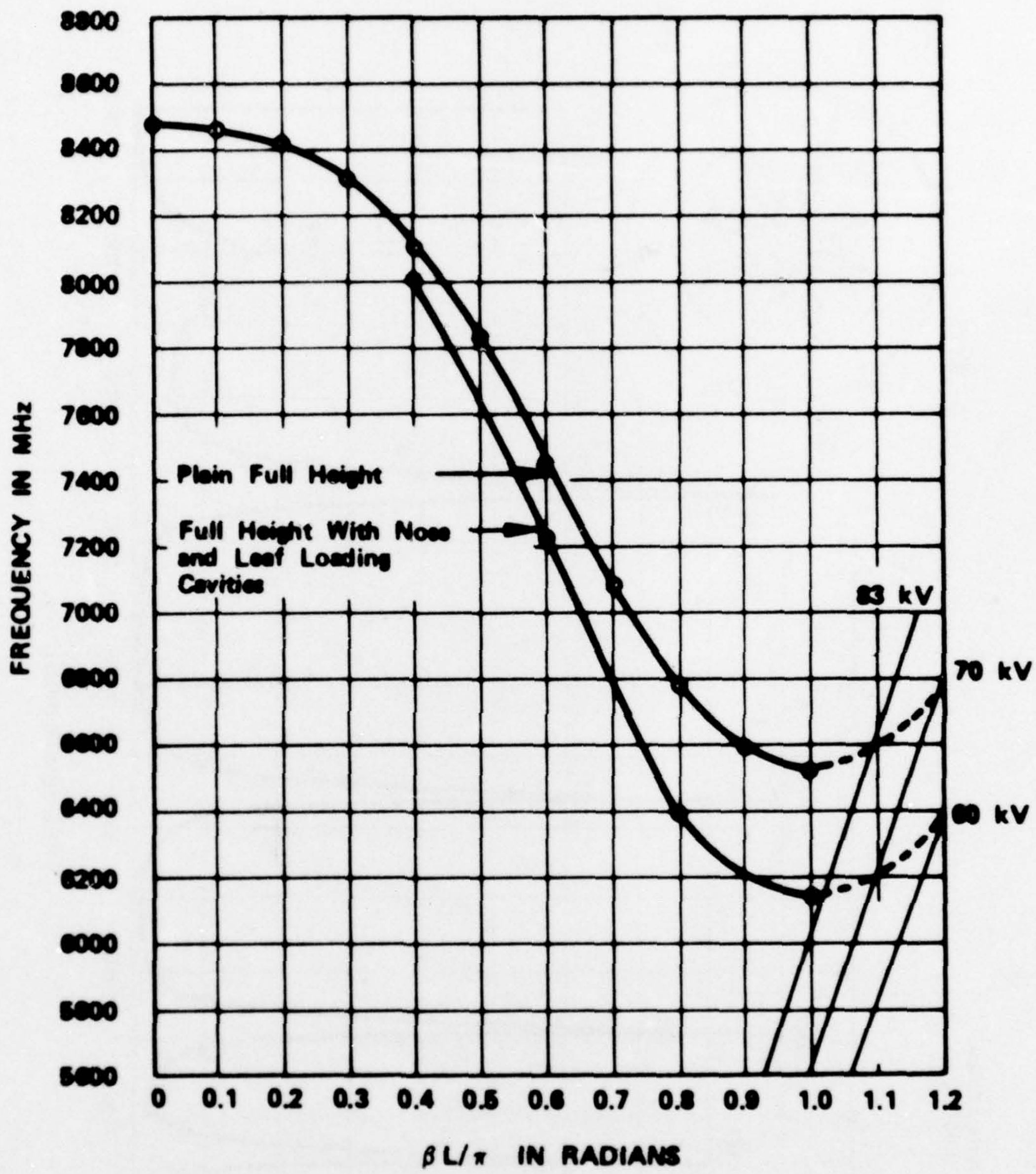


Figure 7. 5H Mode Dispersion Characteristic

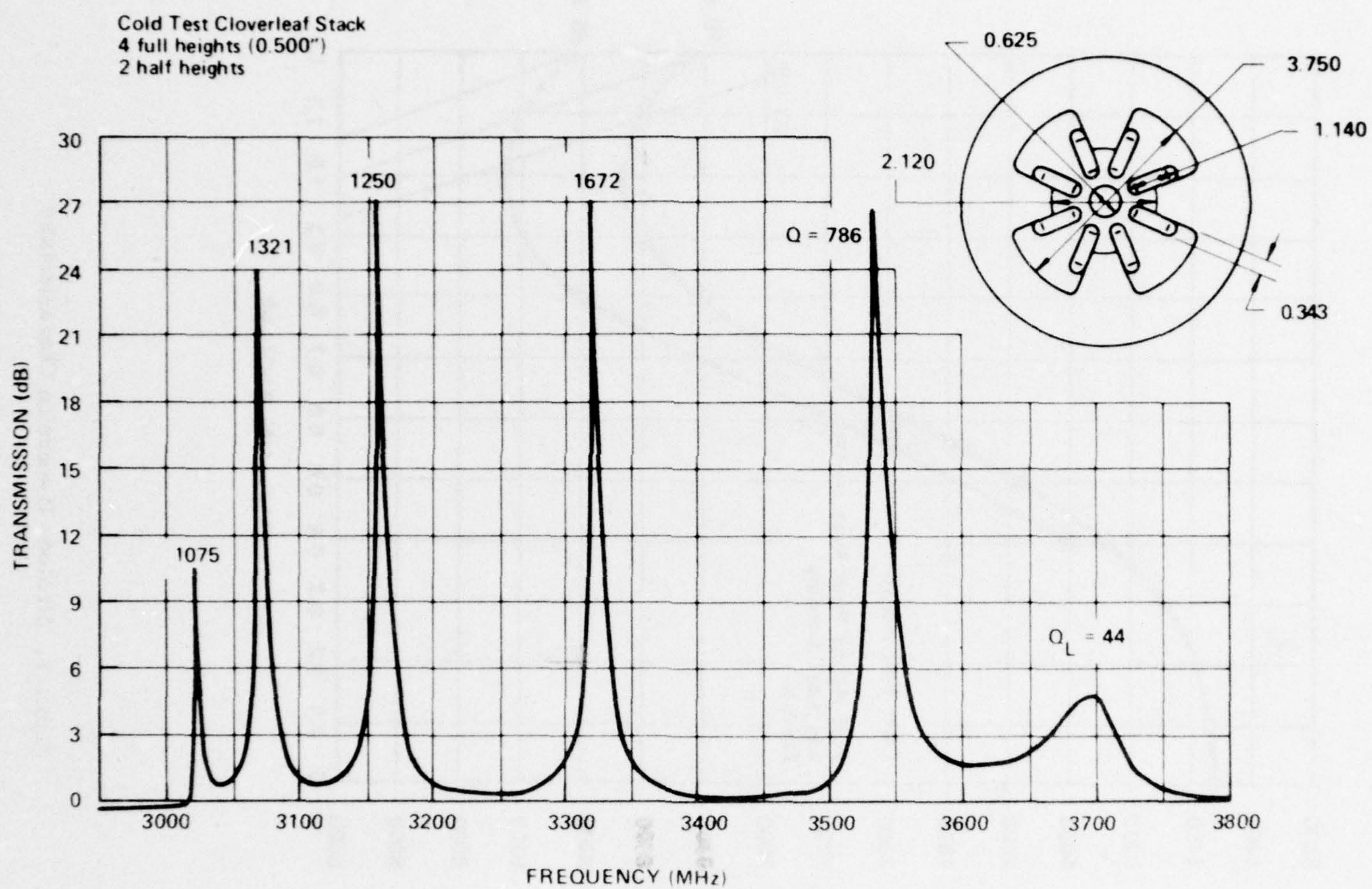


Figure 8. Six-section Stack Resonances

The output window is a thin-disk broadband window and was re-used from Phase II.

The focusing solenoid has six individual wire-wound coils to provide beam control flexibility. Provision has been made for the attachment of a gun coil below the lower polepiece.

H. LARGE SIGNAL ANALYSIS

The modifications to klystron cavities six and seven had no measurable effect on their fundamental mode characteristics so the klystron section input data was unchanged.

The effects of the cloverleaf circuit modifications as described in Section II E of this report were measured in cold test and the data used as inputs to the large signal program.

The beam parameters were changed to those shown in Table 1 and a beam-tunnel filling factor of 0.66 was assumed based on the data described in Section II C.

The normal procedure of reaching a tentative optimum at midband and then doing a broadband analysis was used. Modifications suggested by the large signal analysis were made, cold test data taken, and analysis repeated.

The slight increase in slot length, dictated by the efficiency dip considerations, significantly increased the degree of coupling to the mode loading cavities. There was a minor but measurable effect on the main mode $\omega - \beta$ response due to the main mode, π point loading cavities which required several iterations to resolve.

The decrease in cloverleaf circuit impedance which resulted from the increased slot length led to a maximum predicted efficiency of 51%. The minimum efficiency over a 10% (330 MHz) band was predicted to be 36%. These final computations were made on the time-stepping program.

The computer-predicted efficiency for the final design is shown as a function of frequency in Figure 9. A sample of a computer-generated electron phase plot is shown in Figure 10, with the attendant beam currents and cavity voltages shown in Figure 11.

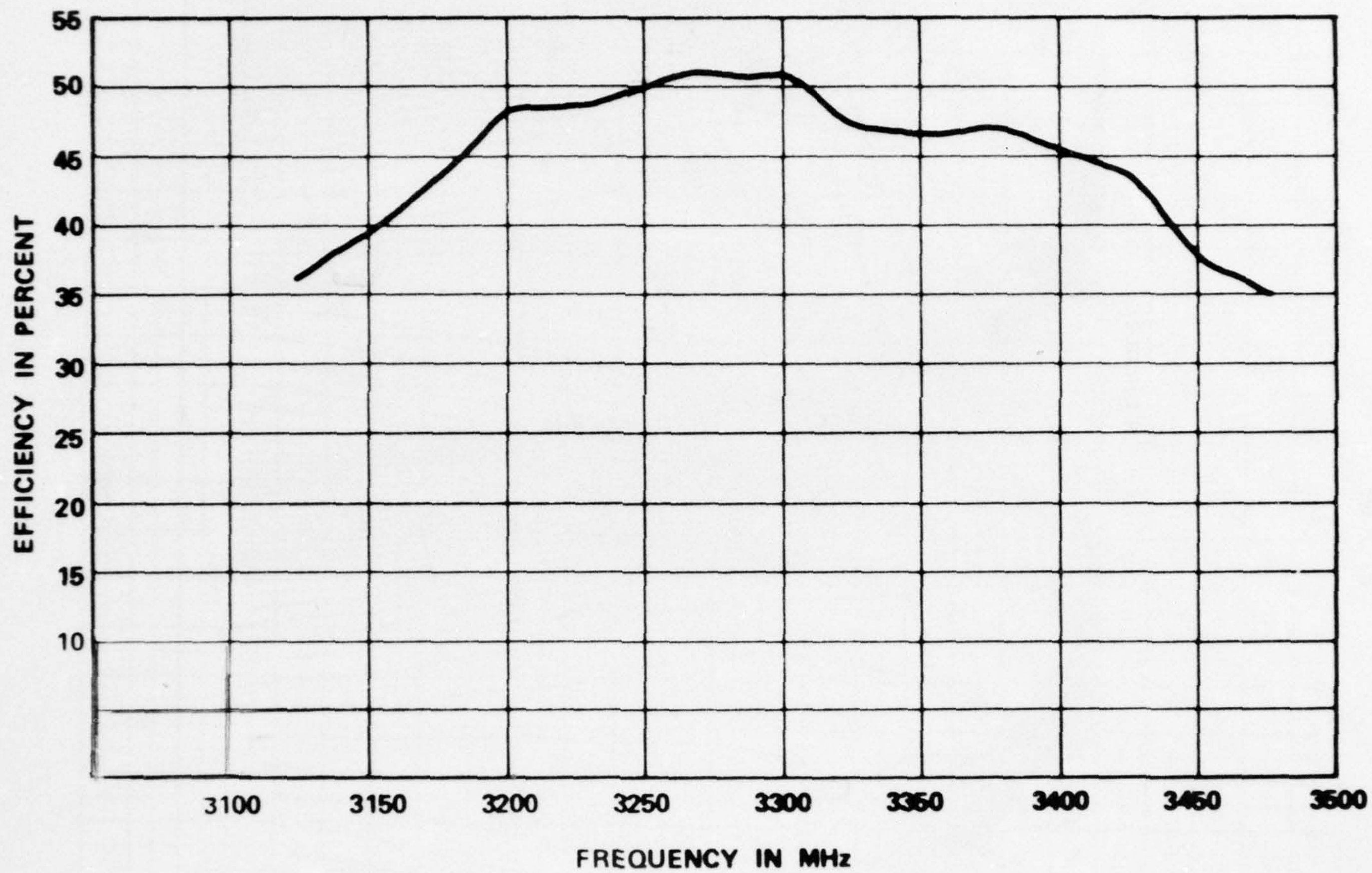


Figure 9. Computer Predicted Efficiency vs Frequency

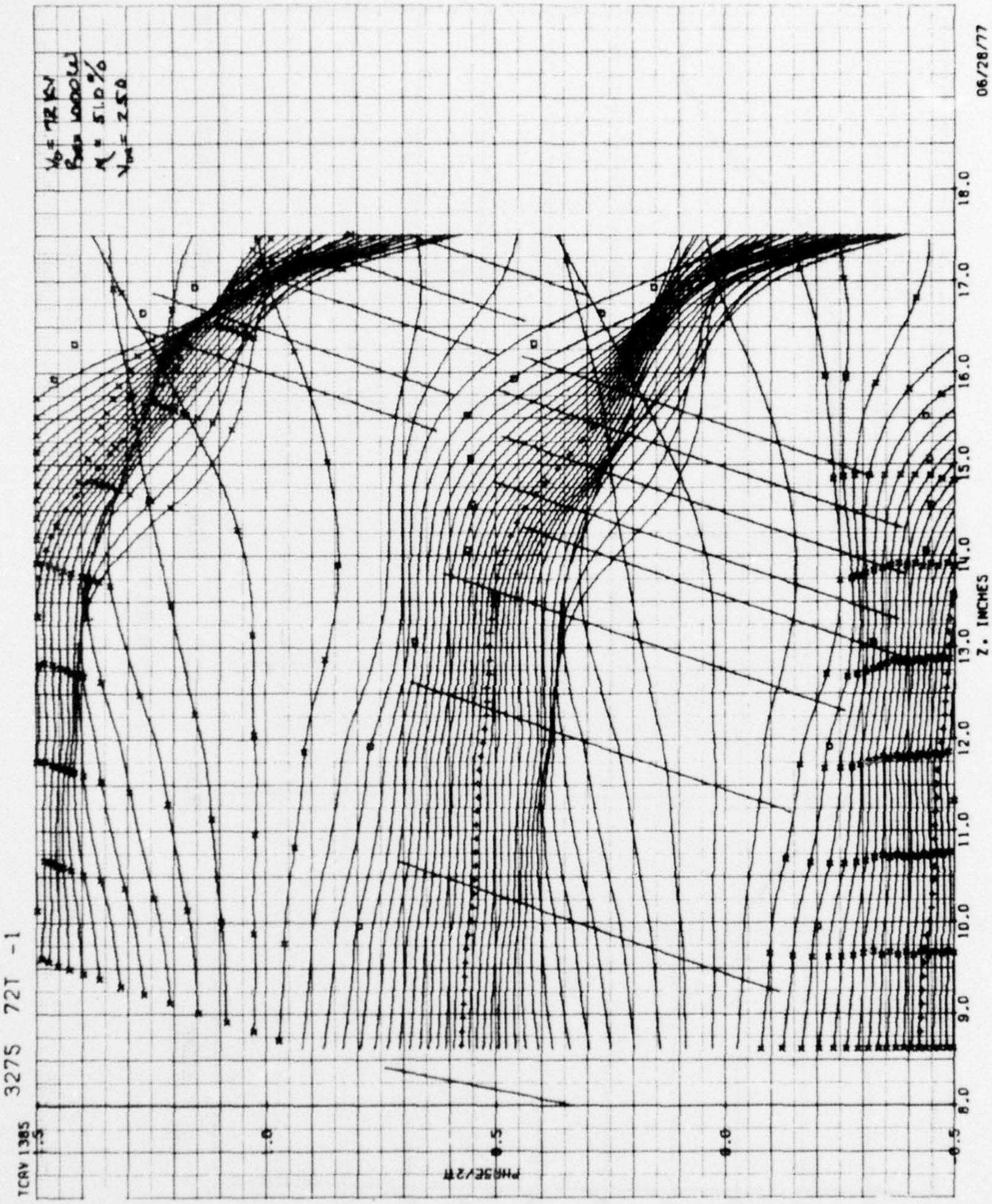


Figure 10. Electron Phase Plot

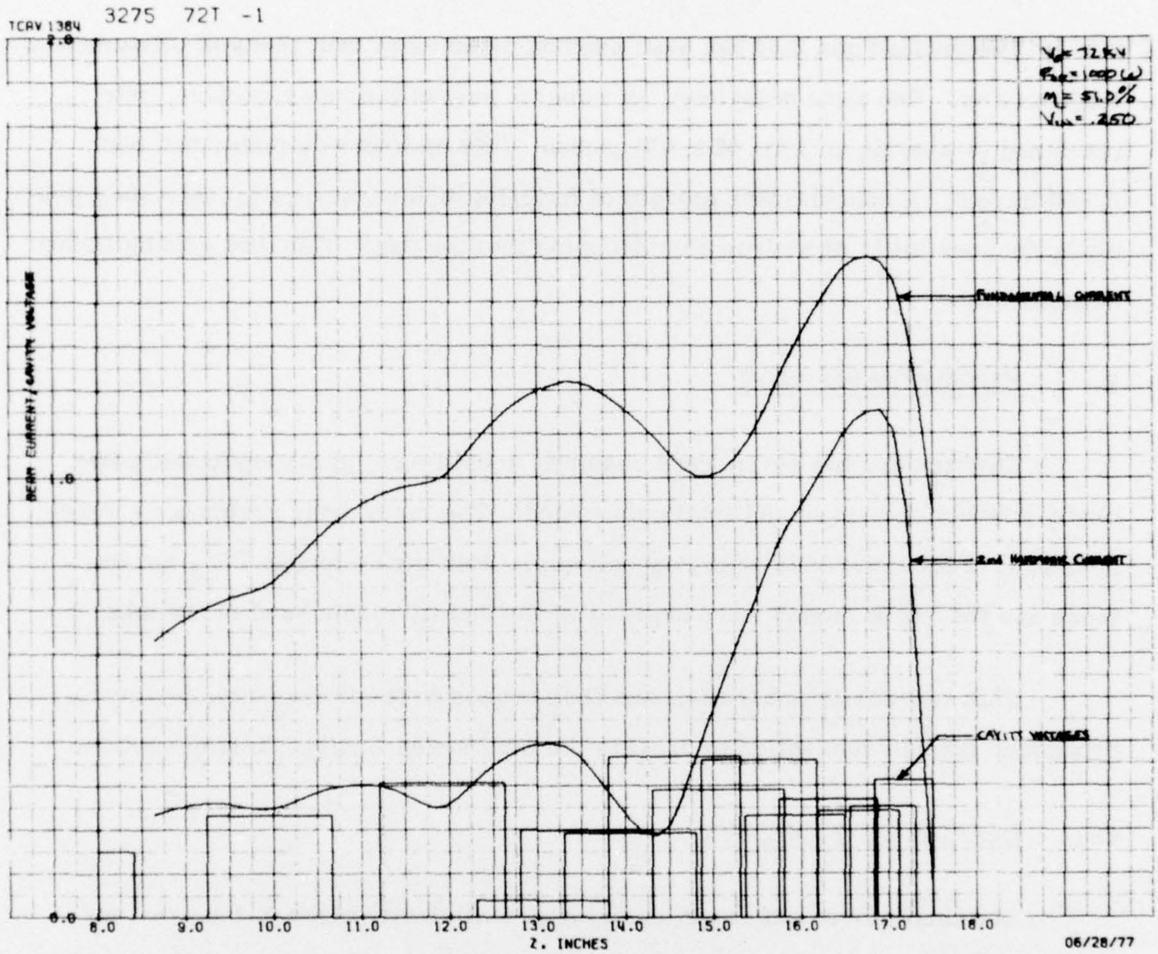


Figure 11. RF Beam Current and Cavity

III. CONSTRUCTION OF EXPERIMENTAL TUBE

A. GRIDDED GUN

The gridded gun that has been used on prior tubes was re-used with one modification. The input polepiece, an integral part of the gun structure, was machined to provide an I. D. of 2.950 inches. The aperture diameter had been 2.750 inches. A considerable amount of fixturing was necessary to absolutely preclude the possibility of an iron chip dropping into the gun. This was accomplished successfully.

B. KLYSTRON SECTION

Cavities six and seven were designed in cold test, parts made and a two cavity subsection brazed and final cold tested. The main mode resonances were held at 3515 MHz and 3525 MHz respectively. Both the distorted TE_{11} coaxial mode and the "split mode" were kept out of the 2nd harmonic band of the tube.

This two-cavity subsection was then brazed to the five-cavity, low level, broadband tunable subsection to provide the final seven-cavity klystron section.

C. CLOVERLEAF OUTPUT

The final cloverleaf cavity design was sufficiently close to the previous design so that the existing templates could be modified and re-used. The cavities are made of OFHC copper with stainless steel tuning posts in the resonant mode-loading cavities. A light coating of Kanthal was applied to the walls of these cavities and to the main circuit area of cloverleaf cavities 5, 6 and 8.

The loading cavities of cloverleaf number 7 were constructed with the tuning posts mounted to thin diaphragms. A simple tuning mechanism was assembled and brazed in place to allow tuning of these loading cavities (4 for main mode π point and two each for the slot and 5Π modes) while the tube was operating

D. OUTPUT AND SEVER TRANSDUCERS

Both transducers provided inductive coupling to the output and sever ports. Subassembly and final assembly brazes caused no difficulties.

E. COLLECTOR

The collector is a standard, water cooled, electrically isolated model.

F. SEVER LOAD

The sever load consists of a BeO-SiC wedge that is metallized and brazed into a reduced height, water cooled, copper waveguide section.

G. OUTPUT WINDOW

The output window is the thin-disk circular window used for the Phase II tube.

IV. TEST RESULTS

A. GENERAL

It had been determined from previous work that there were four areas of deficiency in the performance of the short stack, intense interaction Twystron. They were overall efficiency lower than predicted, marginal stability, a gain hole near the high end of the band, and an efficiency dip near the low end of the band.

Test data taken on this program show that the stability, gain hole and efficiency dip defects have been substantially or completely corrected. The low overall efficiency defect has substantially worsened.

The swept response of the tube with 900 W of rf drive is shown in Figure 12, where a 1.5 dB bandwidth of 9.83% is indicated. The peak efficiency is only 26.6% and the bandedge efficiency is 19%.

The saturated response at this voltage and current is shown in Figure 13, and has a peak efficiency of 30%.

The small signal gain is shown in Figure 14, and the input-output curve at 3300 MHz is shown in Figure 15.

These four figures showing the tube response give a fairly accurate representation of its performance at the design values.

The stability was absolute, even under conditions of overdrive of as much as 10 dB. The 30 dB gain hole has been eliminated. The efficiency dip at the low end of the band is no longer strikingly obvious.

The overall efficiency, however, is only 70% of the levels achieved in the previous version of this Twystron. There is, in addition, a certain lumpiness to the response which is more pronounced than it was previously.

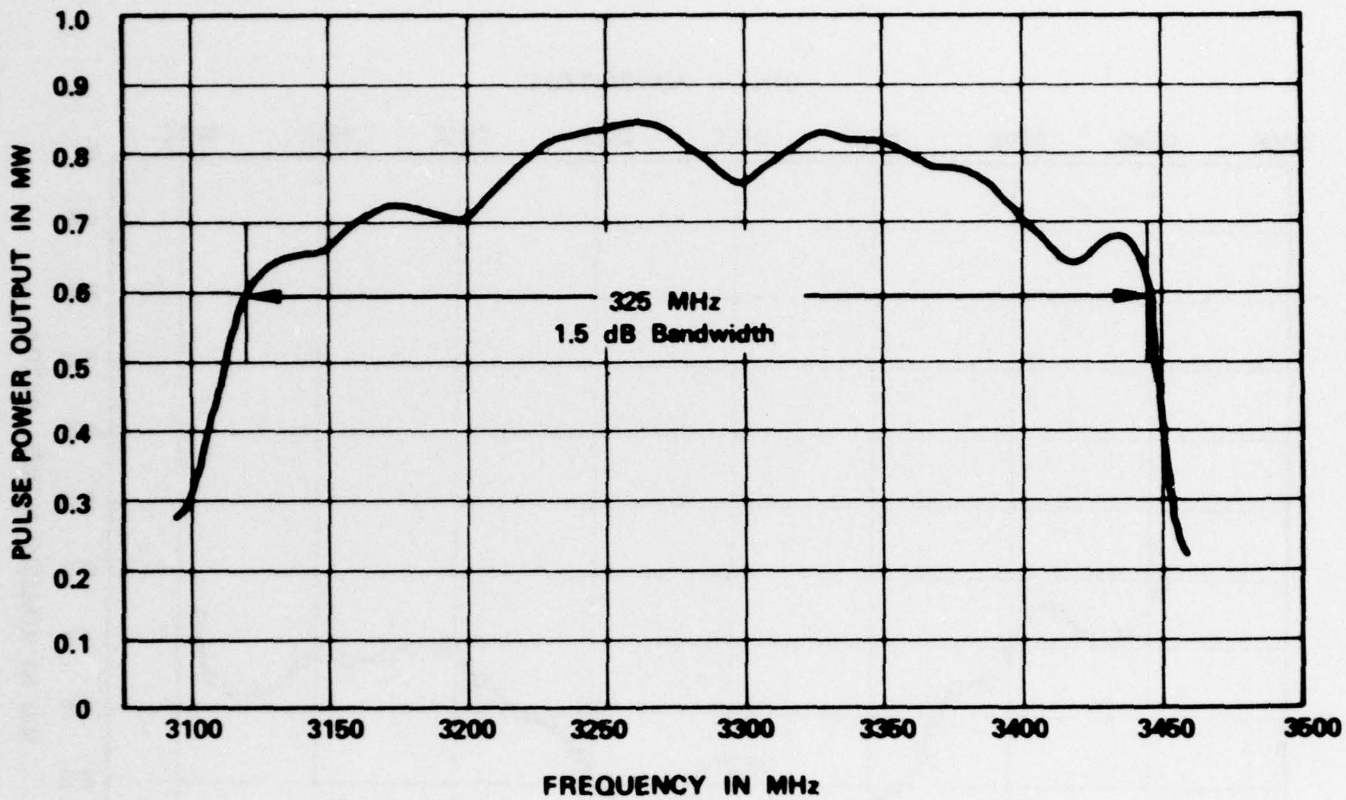


Figure 12. Computer Predicted Power Output vs Frequency

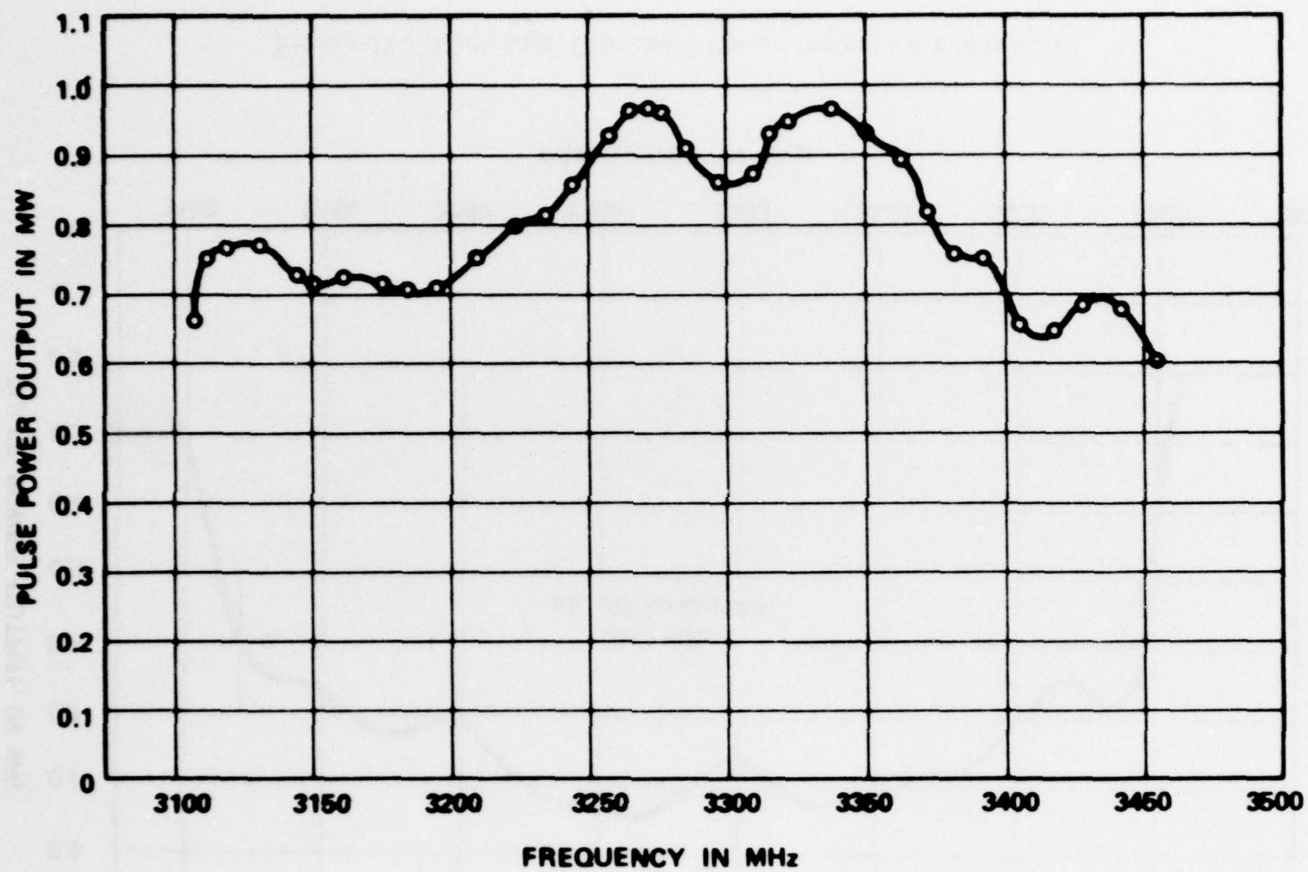


Figure 13. Saturated Power Output vs Frequency at 83 kV and 38 A

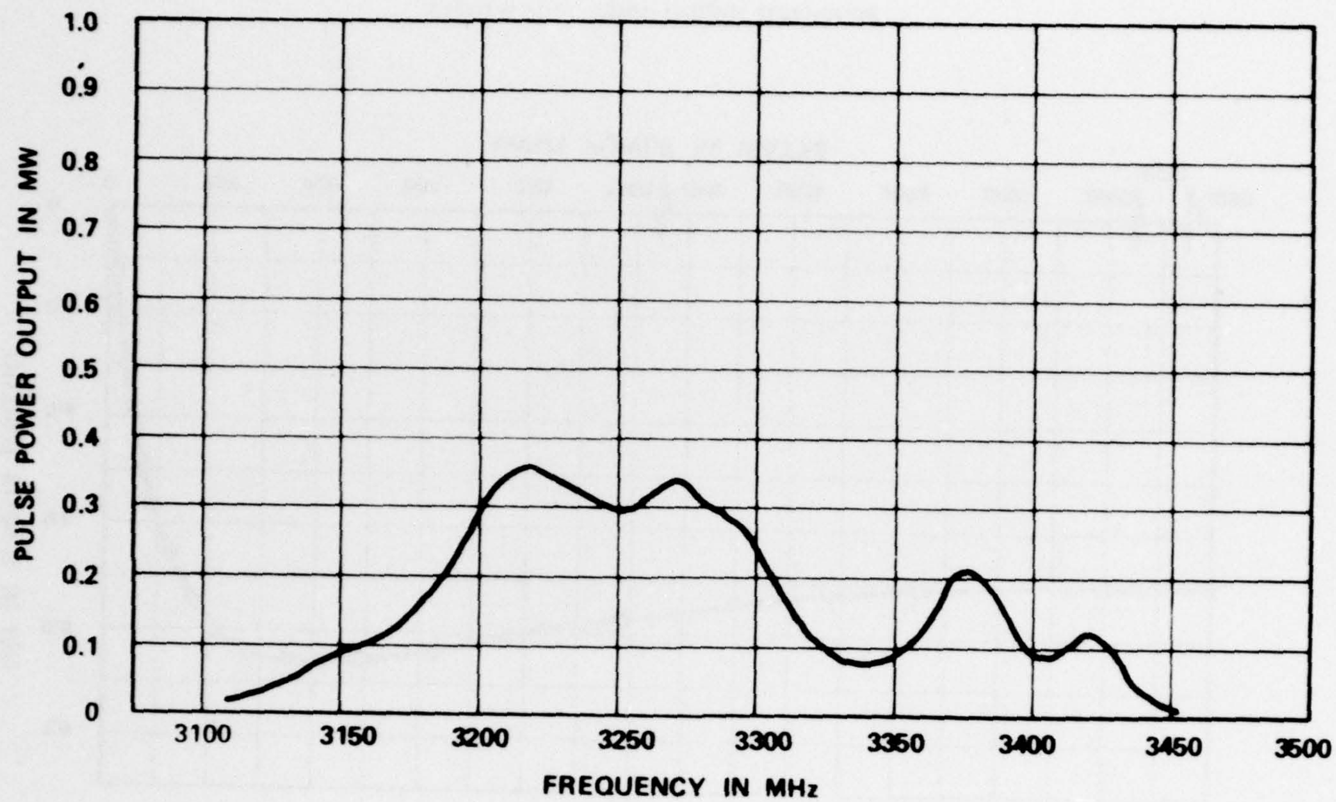


Figure 14. Small Signal Response

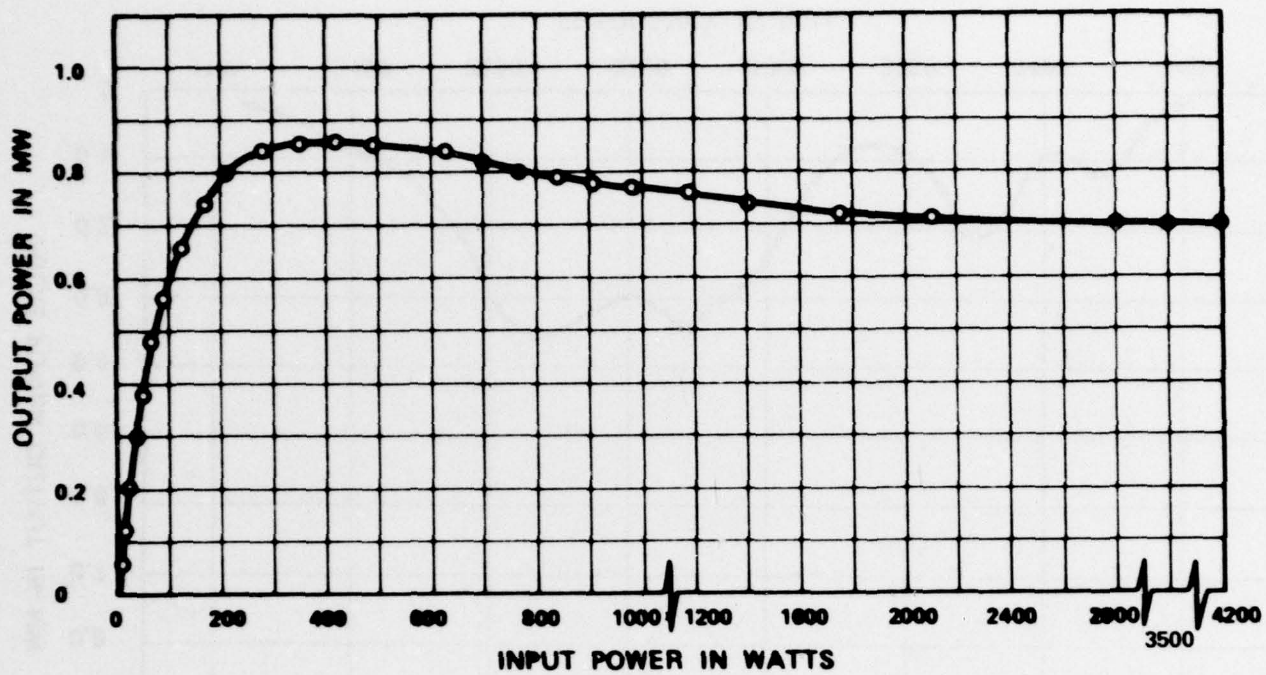


Figure 15. Input-Output Response

B. DETAILED DISCUSSION

1. Efficiency

The overall efficiency achieved was approximately 60% of the effi ciency predicted by large signal analysis. Data was taken over a wide range of voltages and perveances and only minor differences in efficiency were observed. A swept response at 88 kV and microperveance 1.46 is representative of higher voltage operation and is shown in Figure 16. The swept response at 80 kV and microperveance 1.53 is representative of lower voltage operation and is shown in Figure 17. The saturation response for these conditions is shown in Figure 18.

The two most noticeable differences between the present experimental vehicle and previous efforts are in efficiency and beneficial sensitivity to an auxiliary gun coil and reduced microperveance. The efficiency of the present tube is considerably lower than that achieved in previous efforts. The performance of the present tube does not benefit in any significant manner from the addition of aiding or bucking magnetic field in the gun region. In all prior efforts, the efficiency could be increased by reducing the perveance and expanding the beam. The present tube is quite insensitive to perveance. The measured efficiency varied only $\pm$ 1%, in a non-monotonic manner, as the microperveance was varied from 1.59 to 1.09.

The cause or causes of the reduction in efficiency compared to previous efforts must be related to the four modifications incorporated in the present tube. These will be considered in the analysis of results at the end of this section.

2. Broadband Gain

The 30 dB gain hole evidenced on a previous tube was completely eliminated by modifying klystron cavities six and seven and raising the distorted TE_{11} coaxial mode above the 2nd harmonic band of the tube. A constant drive swept

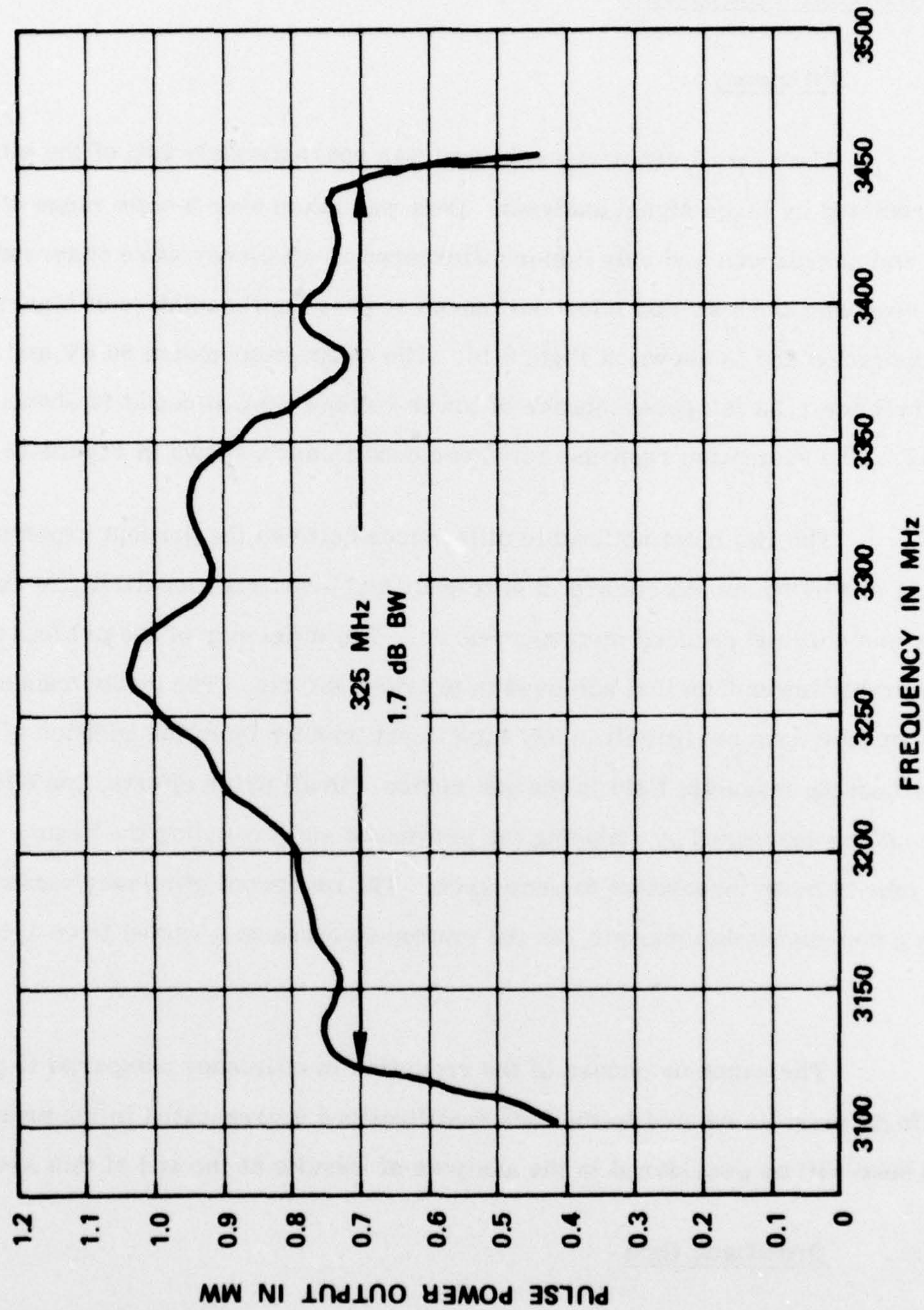


Figure 16. Power Output vs Frequency at 88 kV and 38 A

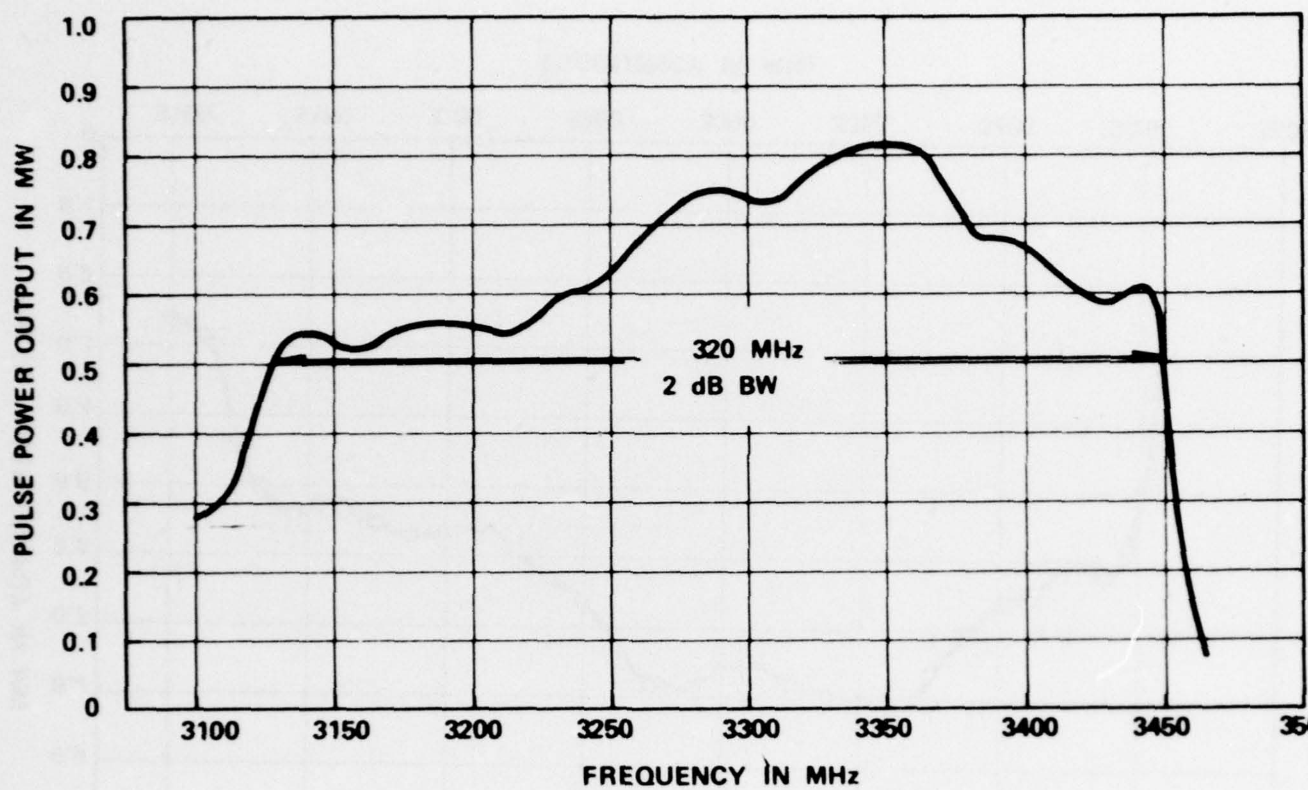


Figure 17. Power Output vs Frequency at 80 kV and 34.7 A

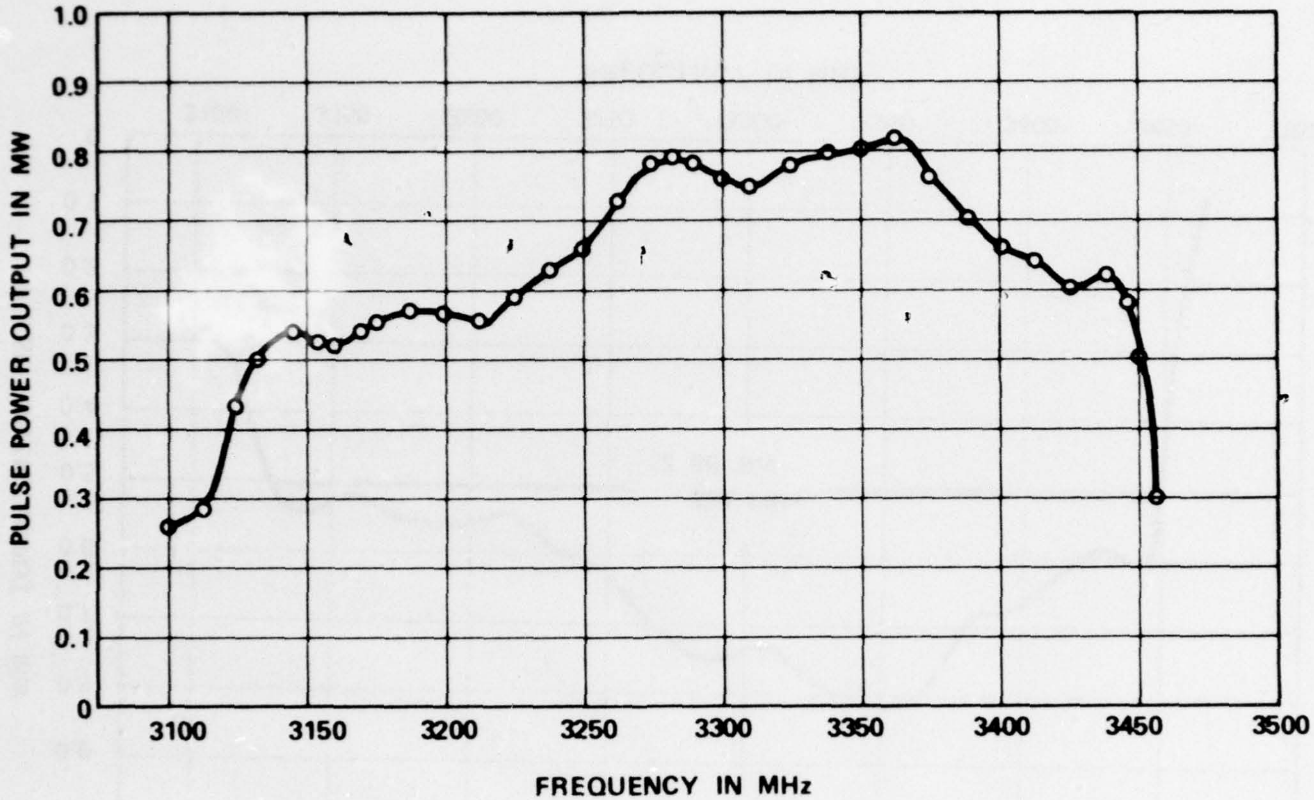


Figure 18. Saturated Power Output vs Frequency at 80 kV and 34.7 A

response of approximately 200 MHz was the best prior effort and was increased to slightly more than 300 MHz on this tube. While the overall level of gain shown is lower than expected, 900 W drive being required, a good deal of gain-bandwidth was sacrificed by tuning dictated by the low efficiency.

The small signal response still suffers from what appears to be insufficient external loading of klystron cavity number three. The cold test measurements, assiduously taken, and the small signal and large signal programs do not indicate this to be the case. Further study is required for resolution of the problem.

3. Stability

The addition of mode loading cavities to a fourth full height cloverleaf circuit has clearly increased the stability of the tube.

Oscillations at the π point of the main mode could be made to occur at beam voltages of 40 kV and below. The necessary perveance to start oscillations at 40 kV was 2.35 micropervs, almost exactly the same as the 2.38 micropervs required in last year's Phase II tube. The tunable π point mode loading cavities were tuned and the perveance required to start oscillation was increased to 2.63 micropervs. The benefit of this increased stability will be an increased tolerance of load mismatch insofar at π point oscillations are concerned.

The goal of stability against drive induced oscillations was also accomplished. There were no indications of any oscillations, even under high overdrive conditions. (10 dB above saturation.)

It must be recognized, however, that if the low efficiency measured is a result of poor beam-circuit coupling, an improvement in this area will also enhance any tendency to oscillate. Since the tube was totally stable with the tunable mode loading cavities in cloverleaf No. 7 completely detuned, there exists considerable margin against any oscillatory tendencies.

4. Analysis of Results

One major problem remains and requires analysis to det its cause and suggest a solution.

The decrease in efficiency from 42% to 30% must have be by one or more of the four (4) modifications made to the design and inco in this program's experimental tube.

The dimensions of klystron cavities 6 and 7 were modifie deleterious higher order modes out of the 2nd harmonic band of the tube damental mode was kept essentially unchanged. There does not appear mechanism whereby this modification could cause a significant decrease ciency across the entire band of the tube.

Lossy, resonant cavities were added to a fourth cloverle Four of the eight lossy cavities in that circuit are set for the π point of mental mode, approximately 3700 MHz. Two of them are set for the sl and were at 4920 MHz and 5100 MHz respectively. The last two are set mode and were at 6260 MHz and 6500 MHz respectively. It was postula these two, tuned within the 2nd harmonic band of the tube, might be des interfering with the bunching. They were tuned well below the harmoni ($\simeq$ 4000 MHz) and no change in efficiency was detected.

The slot lengths were increased by 5 mils to 20 mils; pe increases of 1/2% to 2%. The interaction impedance decreased from 5 465 Ω . (Full height circuit at midband.) This 10% reduction in impec a computer predicted efficiency of 51%, down from 57%. These results sistent with theory and may be considered reasonable. It is possible, that the theory programmed into the computer and/or the mathematical tions programmed are faulty. *It may be that the error increases with* impedance. This, of course, is pure conjecture. It is forced, however, by the fact that only four modifications were made and the first two above do not seem to contain any possible mechanism for adversely affecting the efficiency.

The fourth modification is at least as likely as the slot length increase to have caused the efficiency degradation. The electron beam characteristics have a pronounced effect on all facets of tube performance.

There was evidence from prior work and a review of the original gun design that the beam was smaller than it should be for full interaction. Modifications were made to the magnetic circuit as described in Section II C. The resulting beam had a DC transmission of 98%. The π point stability was unchanged from previous measurements indicating no substantial change in the beam. The effects of an auxiliary gun coil, however, were quite different indicating a substantial change. The stability against drive-induced oscillations at the slot and 5th mode is strong evidence that the beam-circuit interaction decreased. The ability to rf drive the tube to 10 dB beyond saturation is further indication of poor beam-circuit interaction.

While the change in magnetic field, as shown in Figure 2, seems proper and reasonable, it is possible that the original beam was not small, but scalloping badly. The modification may have accentuated this misbehavior.

V. CONCLUSIONS

A. The Twystron designed and built on this program has demonstrated 325 MHz of instantaneous bandwidth. The bandedge efficiency varied from 18% at 0.5 MW minimum power output to 21% at 0.7 MW minimum power output.

B. There were three secondary defects which required correction.

1. The efficiency dip at the low end of the band was reduced in magnitude.

2. The rf drive induced oscillations at and above saturation were eliminated.

3. The gain hole at the upper end of the band was eliminated.

C. The measured efficiencies were only 59% of the values expected. The two possible causes are deemed to be a badly scalloping beam and reduced cloverleaf circuit interaction impedance.

D. Two of the four modifications cured the defects intended and had no deleterious side effects. One or both of the other two, gun and slot length, actually degraded efficiency performance. Had only the beneficial modifications been made, it seems clear that a system-practical device would have resulted.

VI. RECOMMENDATIONS FOR FUTURE EFFORT

The design built and tested on the program just completed contained two modifications, at least one of which degraded tube performance. It is recommended that the tube be demodified, one step at a time.

The more likely cause for the efficiency degradation is the gun modification. It is also fortuitously the simpler task. Should this provide a striking increase in efficiency in the area of 10 percentage points, a new gun should be designed specifically for this tube, incorporating all of the proven advances of the past ten years.

Should the gun de-modification not provide the large increase in efficiency, the cloverleaf output stack should be replaced with the design of the Phase II tube.